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MODULATION AND CODING CONCEPTS FOR HIGH-DEFINITION IMAGING SYSTEMS

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MODULATION AND CODING CONCEPTS FOR HIGH-DEFINITION IMAGING SYSTEMS

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13. ABSTRACT (Maximum 200 words)

There has been considerable world wide research on DTV/HDTV systems. However, the bulk of this work has been concerned with source coding/video compression issues. Only recently has it become apparent that equally important are the transmission issues associated with the design and implementation of appropriate modulation/coding schemes. Indeed, the success of future DTV/HDTV systems will require a judicious combination of efficient video compression techniques together with bandwidth and energy efficient modulation/coding techniques. This report deals primarily with these issues.

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I. Introduction:

There has been considerable world-wide research on DTV/HDTV systems. However, the bulk of this work has been concerned with source coding/video compression issues. Only recently has it become apparent that equally important are the transmission issues associated with the design and implementation of appropriate modulation/coding schemes. Indeed, the success of future DTV/HDTV systems will require a judicious combination of efficient video compression techniques together with bandwidth and energy efficient modulation/coding techniques. Furthermore, appropriate modulation/coding techniques can be expected to be highly specific to the video compression technique employed as well as the delivery media.

The present report summarizes the results of an intensive study of modulation and coding concepts for high-definition imaging systems including DTV/HDTV systems. This study was conducted in the Center for Image Processing Research at Rensselaer Polytechnic Institute (RPI) over the period 2/13/92-9/30/95. The actual results of this study are detailed in a number of reports, papers and Ph.D. theses completed over this period. Rather than duplicate this documentation, the present final report of this effort is written in outline form, indicating the topics investigated, the nature and significance of the results obtained and references to further documentation on each of these topics. A major theme of this research has been to utilize information-theoretic concepts to guide the design and development of modulation/coding approaches for DTV/HDTV systems. The present report will provide selected illustrations of the use of this information-theoretic approach.

II. Preliminaries:

A number of delivery media have been proposed for DTV/HDTV. This has included:

- Direct Broadcast by Satellite (DBS).
- Use of Cable Television Systems (CATV).
- High Speed Digital Subscriber Loops (HSDSL).
- Fiber-Optic Delivery Systems.
- Terrestrial VHF/UHF Broadcast.
- Multiuser Packet-Based Networks.

The modulation/coding issues are decidedly different for each of these delivery systems. For example, the DBS channel is a nonlinear, power-limited transmission channel which dictates the range of applicable modulation/coding schemes. Likewise, the CATV channel is a bandlimited, time-dispersive or intersymbol interference (ISI) channel which suffers from adjacent channel interference effects. Perhaps the most demanding delivery media, however, is represented by the terrestrial VHF/UHF broadcast channel. This is an energy and bandwidth-limited channel which suffers from a number of transmission impairments including: both time and frequency dispersion (fading), spatially distributed interference and adjacent/co-channel interference. The terrestrial VHF/UHF channel should provide the major challenges to modulation/coding design.

A block diagram of a representative DTV/HDTV system for the terrestrial VHF/UHF channel is illustrated in Fig. 1. In general, the encoded video components at the output of the video compression encoder contribute differently to reconstructed video quality and should likewise be treated differentially in the encoding process. This is accomplished in the prioritization and transport encoder where selective error-control protection is provided to the different video encoder output components, as well as encoded audio and data components, on a priority assignment basis. The different priority data streams at the output of the prioritization and transport encoder, ranging from the highest priority (HP) to the lowest priority (LP), are applied to the modulator to produce a composite signal which is then transmitted.

Some of the problems associated with the design of such a system include: video/audio compression scheme, priority assignments of video/audio/data components, modulation/coding scheme and overall performance evaluation. The design and performance evaluation of a robust flexible and extensible overall DTV/HDTV system presents a true engineering challenge. It has been our contention, however, that information-theoretic principles can be quite useful in guiding design choices and tradeoff studies in the development of such systems. Nevertheless, it should be noted that the successes of information-theoretic concepts in guiding the design of communication systems has generally been in the case of single-channel point-to-point links. The DTV/HDTV delivery channel, because of the multiple-priority streams, is neither a single-channel system nor,

because of its broadcast nature, is it a point-to-point channel.

Consider the generic single-channel point-to-point communication system illustrated in Fig. 2. The modulator can be represented as some form of finite-state encoder in cascade with a memoryless modulator. Likewise, the demodulator is represented as a memoryless demodulator, generally a matched filter, in cascade with a decision device which exploits the memory introduced either by the modulator or channel effects. The channel can introduce AWGN, impulse noise (IN), fading/dispersion and adjacent/co-channel interference. Also in Fig. 2, we have included optional interleaving/deinterleaving, scrambling/descrambling and channel state estimation. Assuming that everything within the dotted lines, indicated as the coding channel, is specified and appropriately modeled, it's possible, at least in principle, to develop a complete stochastic description of the resulting coding channel. This then allows an information-theoretic treatment.

Assuming that the coding channel can be appropriately modeled in the single-channel point-to-point communication system of Fig. 2, it's then possible to describe the channel in terms of a number of information-theoretic quantities including the capacity, C, and the cutoff rate, R_0. The capacity represents the largest signaling rate *theoretically* possible while the cutoff rate is generally considered the largest signaling rate *practically* possible. We will find the latter quantity more appropriate for providing a rational tradeoff basis for characterizing practically achievable performance. For example, consider the case of phase-only modulation on the AWGN channel. In Fig. 3 we illustrate the cutoff rate, R_0, of the resulting coding channel in bits/channel use for MPSK modulation with various values of alphabet size M. Also indicated is the limiting cutoff rate for PSK modulation and the E_b/N_0 required to achieve an error probability $P_e = 10^{-5}$, illustrated as circles in Fig. 3, for an uncoded *baseline* system for various M. The basis of trellis-coded modulation (TCM) schemes is the observation that for a baseline uncoded system with $M = 2^m$ it's possible to increase the signaling alphabet size to $M' = 2^{m+1}$, use a rate $R_c = m/m+1$ code and achieve the same throughput, in bits/c.u., without expanding bandwidth. If coded system performance approaching the cutoff rate predictions are possible, this should result in a coding gain determined as the difference in E_b/N_0 for the baseline uncoded system and that to achieve R_0 for

the expanded alphabet coded system operating at the same throughput. In Table 1, we indicate the *potential* coding gains possible through this procedure. It has been established that these potential coding gains can generally be approached rather closely using relatively simple encoder/decoder structures. Similar ideas can be applied to more complicated coding channels as we shall describe.

Before leaving the impression that the single-channel point-to-point communication system in Fig. 2 provides a universal model for DTV/HDTV delivery we should discuss some of its limitations. Consider the representative DTV/HDTV broadcast channel in Fig. 4. Here, each user has a different SNR, and hence different reception quality if a common format transmitted signal is employed, as implied by the single-channel, point-to-point model of Fig. 2. Rather than design for a minimum acceptable reception quality for the weakest, or poorest, user a more reasonable approach would be to tailor the reception quality to the prevailing SNR. For example, suppose that the weakest user is able to receive reliably only the HP transmitted signal which would allow reconstruction of video with a minimally acceptable, or *standard*, quality. The stronger users could then reliably receive additional lower priority class information which would allow reconstruction of improved quality video. If the different priority classes are assigned in a hierarchical multiresolution fashion, this allows a natural way of tailoring the reception quality to the prevailing SNR conditions. The problem is then how to design a hierarchical transmitted signal format with tailored rates $R_1, R_2, \ldots, R_m$ matched to the prevailing SNR. This is a probem in multiuser information theory which provides some guidelines on the design of an appropriate modulation/coding approach.

As an example, suppose that there are two users and it's desired to achieve rates $R_1 = 4$ bits/c.u. and $R_2 = 2$ bits/c.u. Consider then the *embedded* MPSK-based broadcast signaling strategy illustrated in Fig. 5. Here we have a signaling constellation consisting of 4 clouds. User 1 (good) first determines the cloud transmitted and then the particular point within the cloud to achieve $R_1 = 4$ bits/c.u., while User 2 (poor) simply determines which cloud was transmitted to achieve $R_2 = 2$ bits/c.u. Furthermore, suppose there are 2 priority classes. The HP information is used to determine which cloud was transmitted while the LP information determines which constellation point within a

cloud to transmit. User 2 is then able to reconstruct *standard* quality video while User 1 can reconstruct *enhanced* video. In similar fashion, embedded signaling constellations such as this can be designed to provide rates $R_1, R_2, \ldots, R_m$ allowing variable-quality video reconstruction dependent upon prevailing SNR.

While concepts from multiuser information theory provides a useful context for the design of modulation/coding schemes for DTV/HDTV broadcast channels, there has been little done in the way of providing concrete results. As a result, in the remainder of this report we return, despite its limitations, to the single-channel point-to-point model of Fig. 2. Even then there are a number of challenges including: the development of accurate and mathematically tractable stochastic channel models for real-world delivery media such as the terrestrial VHF/UHF channel, the development of techniques for extracting and incorporating channel state information (CSI), the development of reduced-complexity receiver implementations and finally, the incorporation of multielement array processing techniques to combat the effects of spatially distributed interference (SDI). We will discuss each of these selected topics in subsequent sections.

III. Fading Channel Performance:

Consider the case where the physical channel in Fig. 2 is modeled as a slow-fading Rician channel. More specifically, the complex envelope of the channel output signal $r(t)$ is assumed given by

$$\tilde{r}(t) = \tilde{z}(t)\tilde{s}_0(t;\mathbf{c}) + \tilde{n}(t); \tag{1}$$

where $\tilde{s}_0(t;\mathbf{c})$ is the transmitted signal component which depends upon the sequence $\mathbf{c}$ applied as input to the memoryless modulator, $\tilde{n}(t)$ is a complex white Gaussian noise (WGN) process and, finally, $\tilde{z}(t)$ represents the complex fading amplitude. The process $\tilde{z}(t)$ will be assumed to be constant over a signaling interval of duration T_s seconds but allowed to vary from interval-to-interval according to

$$\tilde{z}(t) = \Gamma e^{j\psi} + \tilde{a}_i \ ; \ iT_s \leq t \leq (i+1)T_s, \tag{2}$$

where Γ represents the amplitude of the specular component, ψ is its phase and $\{\tilde{a}_i\}$ is a complex zero-mean Gaussian sequence with variance σ_a^2 described as a first-order autore-

gressive (AR) process with serial correlation $\rho = e^{-2\pi B_0 T_s}$. Here, $B_0 T_s$ represents the Doppler spread normalized to the baud rate and we assume $B_0 T_s \ll 1$. In addition to $B_0 T_s$, the slow-fading Rician channel model is completely defined in terms of the quantity $\varsigma^2 = \Gamma^2/\sigma_a^2$ representing the ratio of specular-to-diffuse energy. Additional details on stochastic modeling of fading channels can be found in [3].

In Fig. 6 we illustrate the cutoff rate R_0 for MPSK signaling on the fully interleaved slow-fading Rician channel when *perfect* channel state information (CSI) is available. Observe the relatively slower but eventual rise to the limiting value $\log_2 M$ bits/c.u. for finite ς^2 compared to the situation with $\varsigma^2 = \infty$, corresponding to the AWGN channel. Again there is the potential here for applying TCM to achieve coding gain without sacrificing bandwidth except that the coding gains are now much more substantial than in the case of the AWGN channel. On the other hand, when *no* CSI is available the quantity ς^2 sets an upper limit on the achievable R_0. This limiting value of R_0 as a function of ς^2 is illustrated in Fig. 7. Observe, for example, that if $\varsigma^2 = 10$dB, throughputs in excess of 3 bits/c.u. are impossible to achieve. This absence of CSI severely limits the ability to apply coding to an expanded alphabet in an effort to achieve coding gain without sacrificing bandwidth.

In Table 2 we illustrate potential coding gains available on the slow-fading Rician channel both with and without CSI. Here the asterisk "*" denotes that performance with or without coding is not available at this throughput while "∞" indicates that this throughput is available with coding but not possible for an uncoded system. Notice the substantial coding gains possible with *perfect* CSI relative to the *no* CSI case. This points out the importance of CSI on fading channels. Finally, it should be noted that these potential coding gains can be approached rather closely with moderate complexity [3].

The details of the explicit evaluation of R_0 for fading channels is documented in a number of places, including the two Ph.D. theses [3, 4] and the two journal papers [5, 6] to which the interested reader is referred.

IV. Estimation of Channel State Information:

Consider the channel decoder in Fig. 2 and several options for its implementation. For example, in the case of *perfect* CSI the maximum-likelihood (ML) decoding rule is given by

$$\hat{\mathbf{a}}_{ML,ps} = \arg\max_{\mathbf{a}} p(\tilde{\mathbf{r}}|\mathbf{a}, \tilde{\mathbf{z}}), \tag{3}$$

where $p(\tilde{\mathbf{r}}|\mathbf{a}, \tilde{\mathbf{z}})$ represents the conditional probability of the output sequence $\tilde{\mathbf{r}}$ appearing at the output of the coding channel given the input sequence $\mathbf{a}$ and the sequence $\tilde{\mathbf{z}}$ of complex fading amplitudes representing CSI. On the other hand, for the case of *no* CSI, the ML decoding rule is

$$\hat{\mathbf{a}}_{ML,ns} = \arg\max_{\mathbf{a}} p(\tilde{\mathbf{r}}|\mathbf{a}), \tag{4}$$

where now

$$p(\tilde{\mathbf{r}}|\mathbf{a}) = \int p(\tilde{\mathbf{r}}|\mathbf{a}, \tilde{\mathbf{z}}) p(\tilde{\mathbf{z}}) d\tilde{\mathbf{z}}. \tag{5}$$

This leads to decidedly inferior performance as discussed in the preceding section. As an alternative, we could consider the case where we make use of the ML decoding rule for *perfect* CSI but instead replace the true but unknown value of $\tilde{\mathbf{z}}$ by an estimated value $\hat{\tilde{\mathbf{z}}}$. This leads to the ML decoding rule using *estimated* CSI given by

$$\hat{\mathbf{a}}_{ML,es} = \arg\max_{\mathbf{a}} p(\tilde{\mathbf{r}}|\mathbf{a}, \hat{\tilde{\mathbf{z}}}). \tag{6}$$

One method for obtaining $\hat{\tilde{\mathbf{z}}}$ is based upon the use of the expectation-maximum (EM) algorithm. Here, we let the observations $\tilde{\mathbf{r}}$ represent *incomplete* data and $\mathbf{y} = (\tilde{\mathbf{r}}, \tilde{\mathbf{z}})$ represent *complete* but unobservable data. The EM algorithm is an iterative method of parameter estimation based upon incomplete data which makes essential use of the simpler complete data statistical description. Furthermore, as a byproduct, it generally provides an estimate of the missing data, or $\tilde{\mathbf{z}}$ in this case.

A block diagram of an EM-based method for iterative simultaneous decoding and channel state estimation on the slow-fading Rician channel is illustrated in Fig. 8 [7].

We assume MPSK modulation and the availability of initial estimates $\hat{\mathbf{z}}_0$ of the channel state together with initial estimates $\hat{\mathbf{c}}_0$ of the transmitted sequence. These are used in the EM algorithm together with the demodulator output sequence to produce the sequence of estimates $\{\hat{\mathbf{z}}_p\}$ of the channel state. These estimates are then used in the channel decoder, implemented using the Viterbi algorithm (VA), to produce the sequence of symbol estimates $\{\hat{\mathbf{c}}_p\}$. After convergence the estimated information sequence is released to the remote destination.

In Fig. 9 we illustrate typical results for 8PSK TCM using an 8-state encoder with code vector (9,2,4) operating on the slow-fading Rician channel with $\varsigma^2 = 10$ dB for different values of B_0T_s. Computed upper bounds on bit error probability performance are also provided for the two extremes of *perfect* and *no* CSI together with corresponding simulation results. Observe that for the relatively slow-fading case $B_0T_s = 0.1$, results using the EM algorithm are quite close to the *perfect* CSI results. For the case $B_0T_s = 0.1$, representing relatively faster fading, the simulation results using the EM algorithm are intermediate between the *perfect* and *no* CSI cases. Thus, for relatively slow fading ($B_0T_s < 0.1$), this EM-based scheme for simultaneous decoding and channel state estimation is capable of performance close to that with *perfect* CSI.

A complete treatment of the development and analysis of this EM-based method for iterative simultaneous decoding and channel state estimation is provided in [3, 7].

V. Reduced-Complexity Receiver Structures

A block diagram of a model for sequence transmission over an intersymbol interference (ISI) channel is illustrated in Fig. 10. The complex sequence $\tilde{\mathbf{c}} = (\tilde{c}_{-K}, ..., \tilde{c}_{-1}, \tilde{c}_0, \tilde{c}_1, ..., \tilde{c}_K)$ is to be transmitted over a channel consisting of the cascade combination of a pulse shaping filter with impulse response $\tilde{g}(t)$ and a channel filter with impulse response $\tilde{h}_c(t)$. The overall response is then $\tilde{h}(t) = \tilde{g}(t) \otimes \tilde{h}_c(t)$. The received signal is of the form

$$\tilde{r}(t) = \tilde{s}_o(t; \tilde{\mathbf{c}}) + \tilde{n}(t), \tag{7}$$

where $\tilde{n}(t)$ is complex AWGN and

$$\tilde{s}_o(t;\tilde{\mathbf{c}}) = \sum_{k=-K}^{K} \tilde{c}_r \tilde{h}(t - kT_s), \tag{8}$$

with T_s the channel signaling interval.

The conventional maximum-likelihood sequence estimator (MLSE) for recovering an estimate $\tilde{\mathbf{c}}$ of the transmitted sequence is illustrated in Fig. 11. It consists of a conventional matched filter, matched to the overall response $\tilde{h}(t)$, whose output is sampled at the symbol rate $f_s = 1/T_s$. The resulting discrete sequence $\{\tilde{r}_r\}$ is applied to a whitening filter, which makes use of the assumed known ISI matrix $\mathbf{H}$, whose whitened output is applied to a sequence estimator employing the Viterbi algorithm (VA).

The complexity of this VA-based MLSE is proportional to M^L where M is the size of the symbol alphabet and L is the delay dispersion of the channel filter. This exponential dependency upon L renders the VA-based MLSE impractical for large M and/or L. To avoid this exponential complexity in L, we have developed a novel iterative MLSE based upon the EM algorithm and illustrated in Fig. 12. Extensive simulation results have demonstrated that rather than the exponential complexity of the VA-based MLSE, the EM-based MLSE exhibits complexity which is only linear in L. This provides a tremendous computational advantage over the VA-based approach.

The details on the development and performance of the EM-based MLSE are provided in [8, 9].

VI. Multielement Array Processing

A major source of intereference in VHF/UHF terrestrial broadcasting is due to spatially-distributed intereference (SDI). The use of multielement array processing techniques are well-known to be effective in combatting this type of interference. It is less well known, however, that combinations of modulation/coding together with multielement array processing can provide for superior performances over either approach acting alone.

The use of multielement array processing can easily be included in the single-channel point-to-point model of Fig. 2. The channel output $r(t)$ is merely replaced by

the vector $\mathbf{r}(t) = (r_1(t), r_2(t), ..r_N(t))$ representing the individual array element outputs. Likewise, the demodulator is replaced by an optimum integrated ML array processor/demodulator as described in [10]. A block diagram of this optimum ML processor is illustrated in Fig. 13. Thus, given the array geometry and the interference environment, and assuming the use of the optimum ML spatio-temporal array processor, it is possible to again provide a complete stochastic description of the coding channel. This allows an information-theoretic treatment as in the case of single-element reception. In particular, it is possible to compute the cutoff vector R_0 [11].

In Fig. 14 we illustrate the cutoff rate performance for QAM using various linear array processing structures with half-wavelength interelement spacing. For this particular case we assume that a single interferrer is present at $\theta_1 = 16°$ from boresight. The interference signal is modeled as Gaussian with first-order Butterworth spectrum whose 3 dB bandwidth f_1 normalized to the baud rate is $f_1 T_s = 1.0$ and whose strength is 20 dB above the background AWGN. Results are illustrated in Fig. 14 for $N = 1, 2$ and 4 as well as the case for no interference or AWGN alone. We have also indicated with asterisks the E_b/N_0 required by a baseline uncoded system to achieve $P_e = 10^{-5}$ for different alphabet size M.

From the cutoff rate curves in Fig. 14, it should be clear that TCM could be used, together with multielement array processing, to combat the effects of SDI. In Table 3 we illustrate potential coding gains possible for this example using TCM together with ML array processing for different throughputs in bits/c.u. For example, at 2 bits/c.u., a potential coding gain of 15.6 dB is possible using a single-element array and TCM alone by expanding the bandwidth from $M = 4$ to $M = 8$. On the other hand, this can be increased to 22.7 and 27.6 dB using TCM together with 2 and 4 element array processing, respectively. The limiting coding gain is 29.1 dB if all sources of SDI could be removed (AWGN alone) so that the 4-element array comes close to achieving the maximum potential coding gain.

Further details on the use of multielement array processing for this application can be found in [12, 13].

VII. Summary

We have attempted to provide a summary of some of the important modulation/coding issues for DTV/HDTV. In particular, we have attempted to show how information-theroetic concepts can be useful in developing an objective design and performance analysis methodology and have illustrated this approach through some selected examples important for the VHF/UHF terrestrial broadcast channel. While we have touched on some issues, much more remains to be done in completely characterizing the modulation/coding issues associated with DTV/HDTV. Indeed, the design and performance analysis of robust, flexible and extensible DTV/HDTV transmission systems presents a true engineering challenge. The results reported here provide a first significant step in this direction.

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Baseline System	Coding Gain
2-PSK	8.1 dB
4-PSK	5.9 dB
8-PSK	5.6 dB
16-PSK	5.4 dB

Table 1: Potential Coding Gains Using MPSK on the AWGN Channel.

Throughput in bits/c.u. m	Perfect CSI					No CSI		
	ζ^2					ζ^2		
	AWGN	15 dB	10 dB	7 dB	0	AWGN	20 dB	15 dB
1	8.1 dB	9.7 dB	16.4 dB	24.1 dB	48.9 dB	8.1 dB	8.5 dB	10.0 dB
2	5.9	7.6	13.9	23.0	47.7	5.9	7.0	11.2
3	5.6	7.3	13.3	22.7	48.5	5.6	11.3	∞
4	5.4	7.2	13.0	22.3	46.6	5.4	∞	$\star$

Table 2: Potential Coding Gains Achievable on the Slow-Fading Rician Channel With Ideal Interleaving/Deinterleaving.

Throughput in bits/c.u. m	Single-Element Array	Two-Element Array	Four-Element Array	AWGN Alone
1	13.5 dB	20.6 dB	25.6 dB	27.0 dB
2	15.6	22.7	27.6	29.1
3	17.9	24.9	29.9	31.5
4	20.4	27.5	32.5	34.0
5	23.0	30.1	35.0	36.6

Table 3: Potential Coding Gains for QAM Using Coding Together with ML Multielement Array Processing.

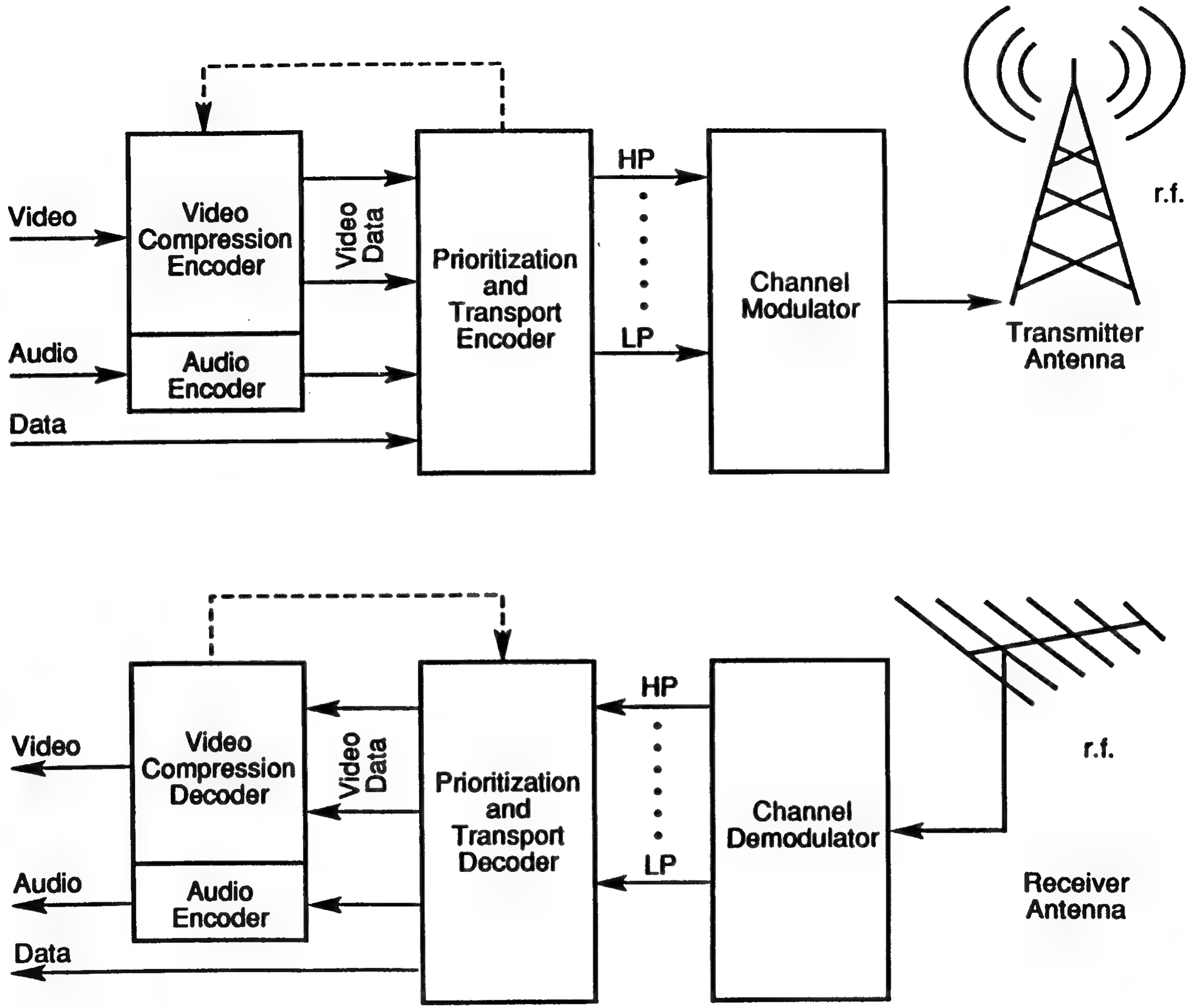

Figure 1
Representative DTV/HDTV system for terrestrial VHF/UHF channel.

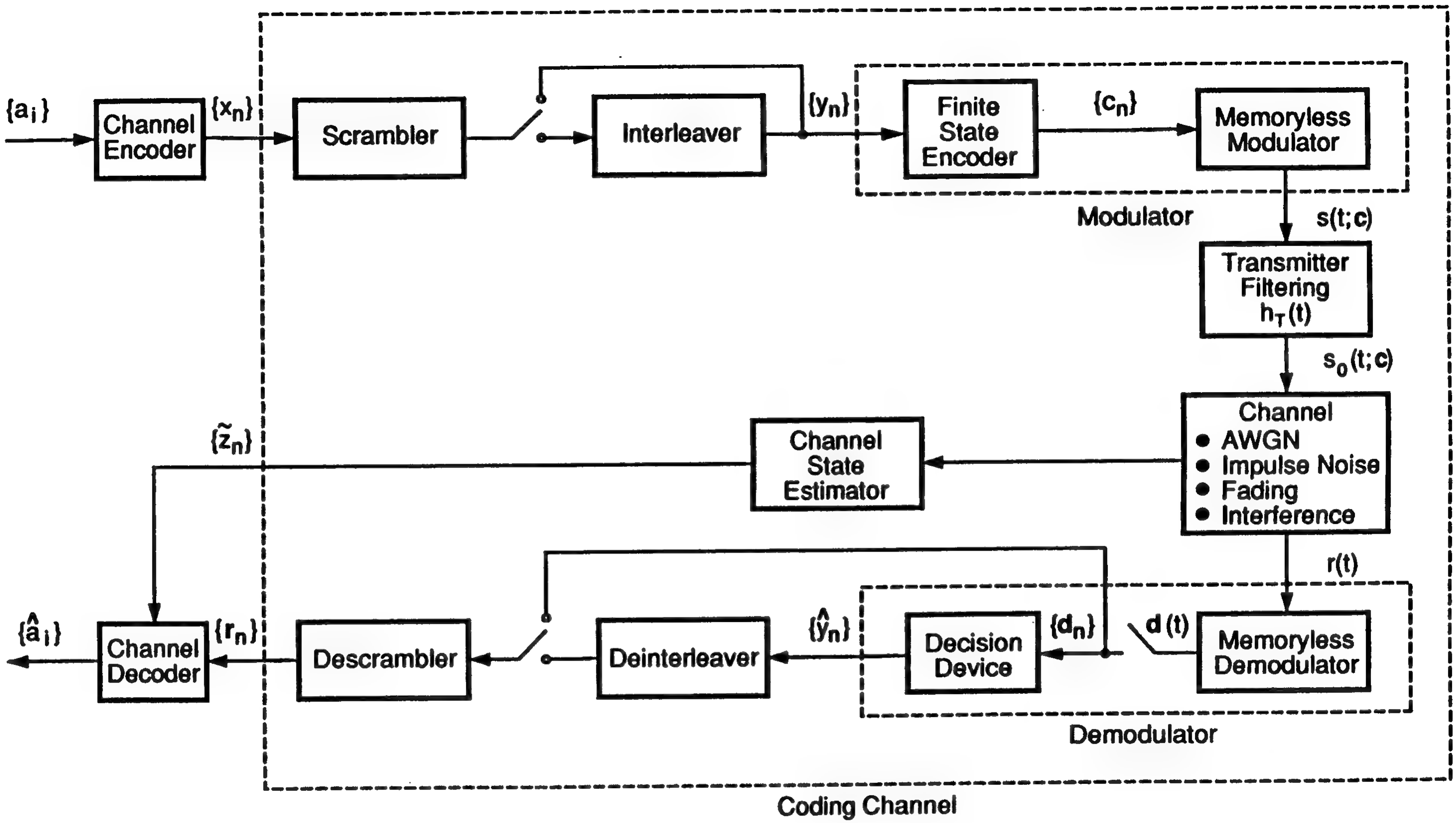

Figure 2
Generic coded communication system.

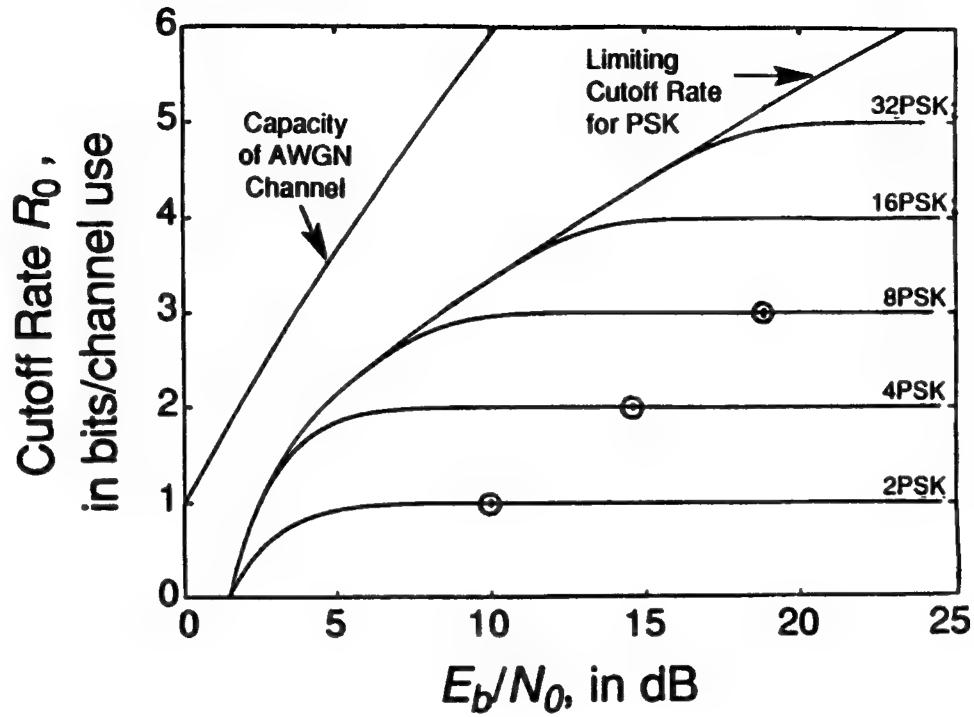

Figure 3
Cutoff rate performance for MPSK modulation on the AWGN channel.

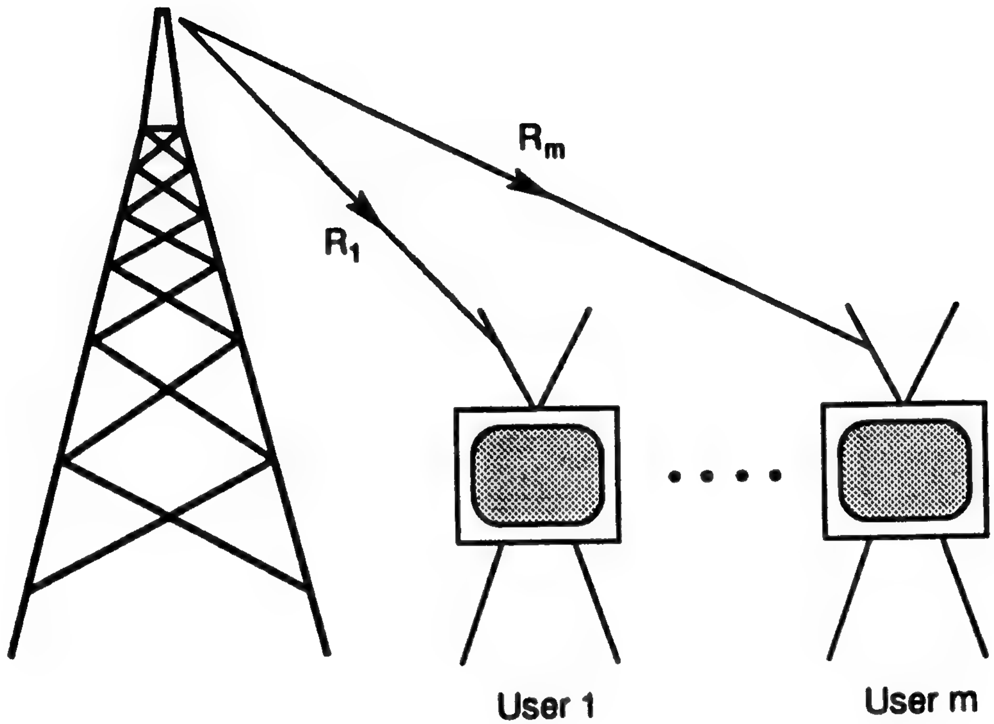

Figure 4
Typical DTV broadcast channel.

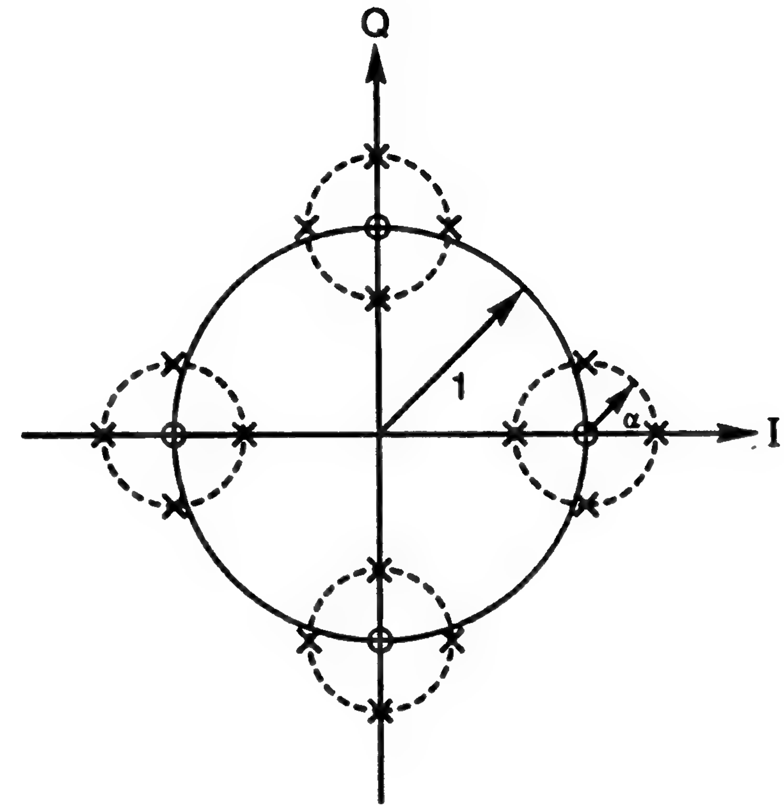

Figure 5
Signalling constellation for two-level coarse/fine broadcast transmission strategy.

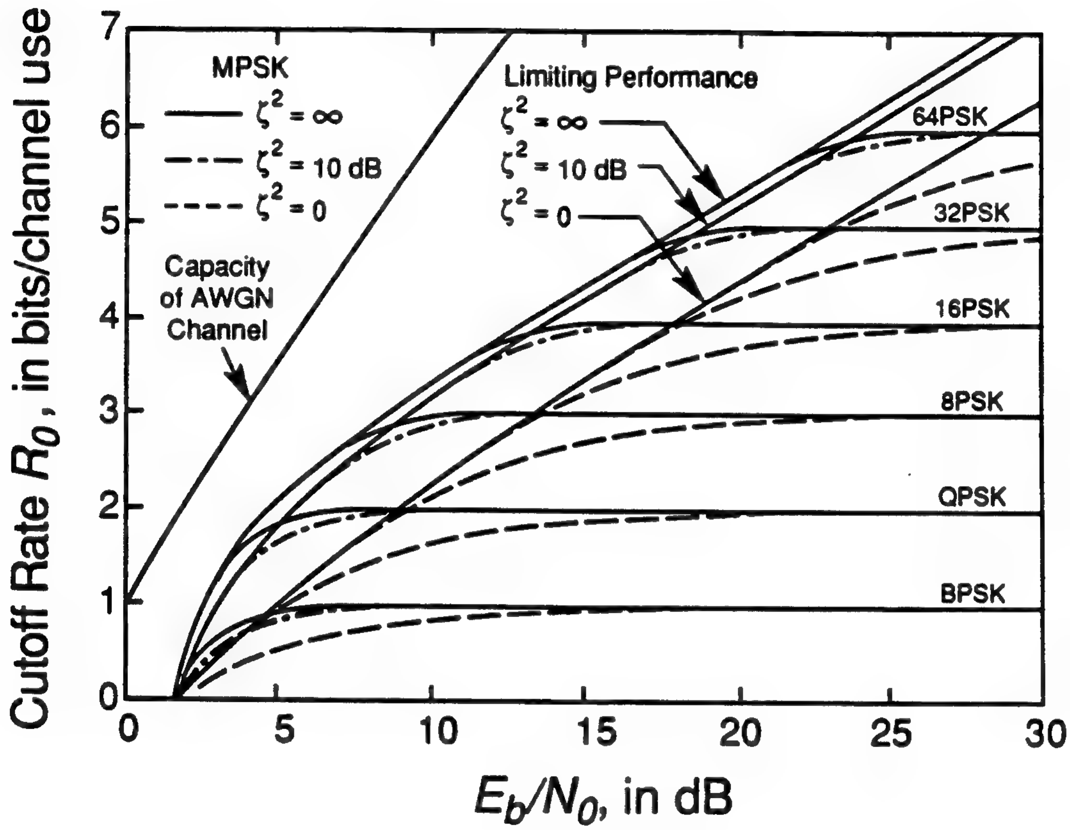

Figure 6
Cutoff rate performance for interleaved Rician channel with perfect CSI.

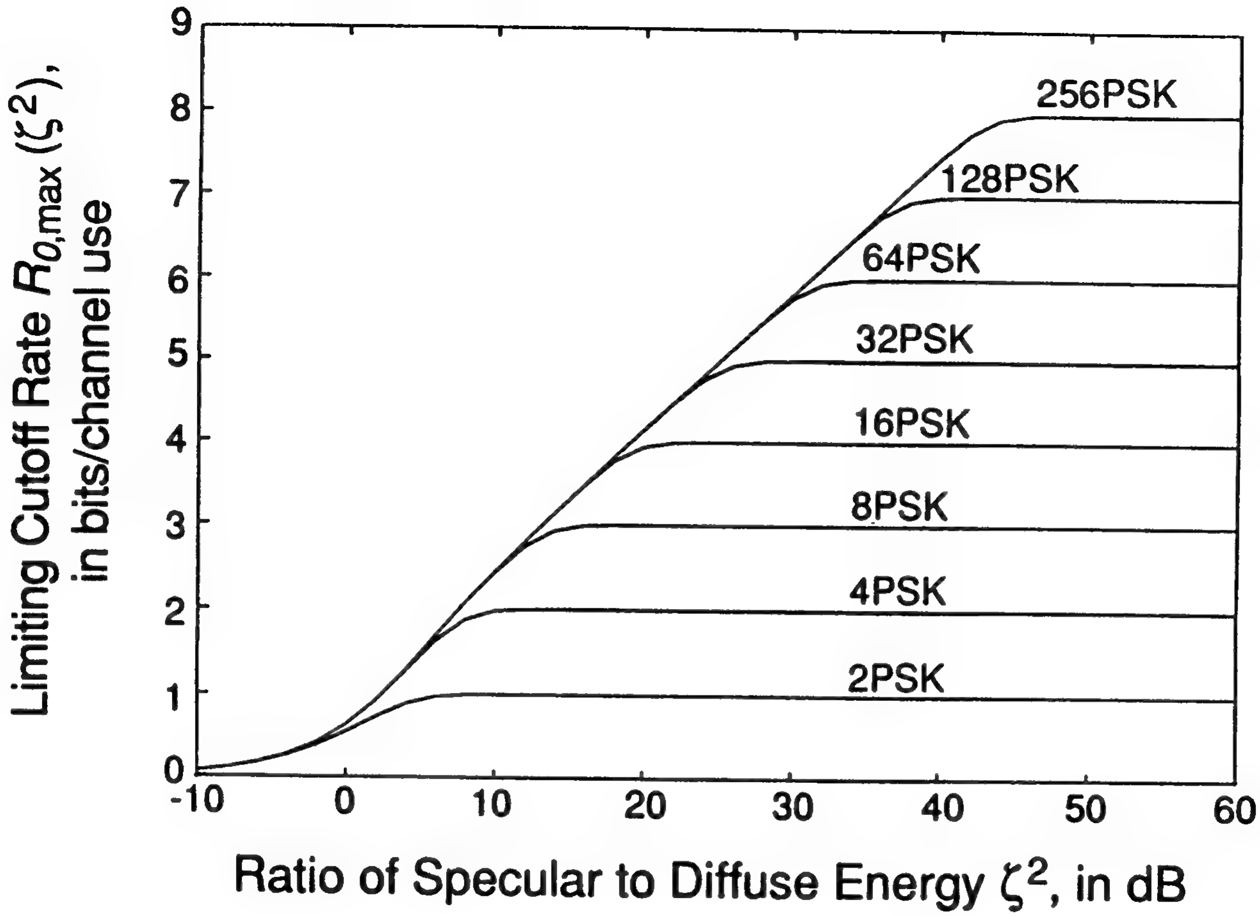

Figure 7

Behavior of limiting cutoff rate for phase-only modulation on the interleaved Rician channel with no CSI.

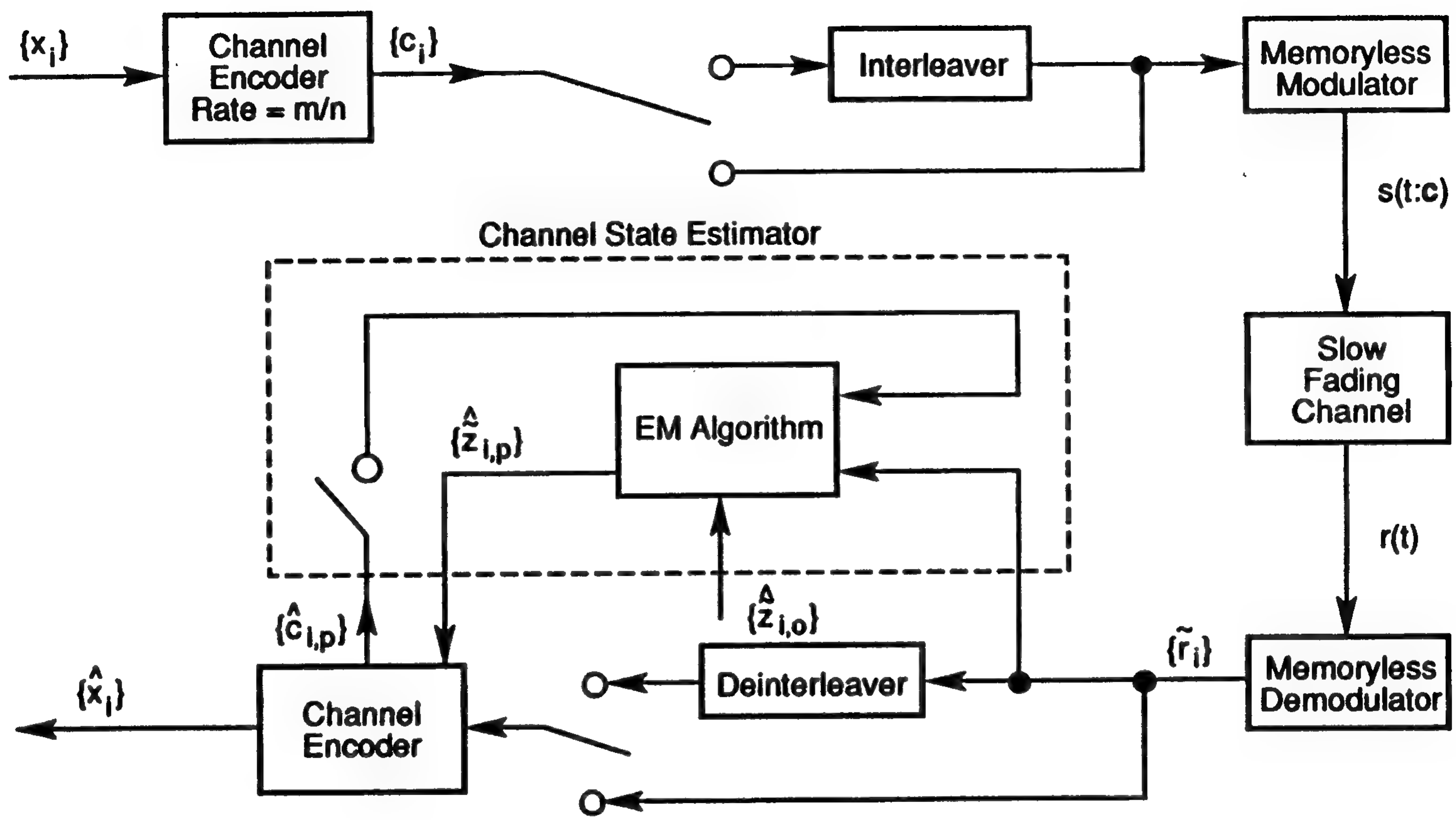

Figure 8
Iterative simultaneous decoding and channel state estimation on the slow-fading Rician channel.

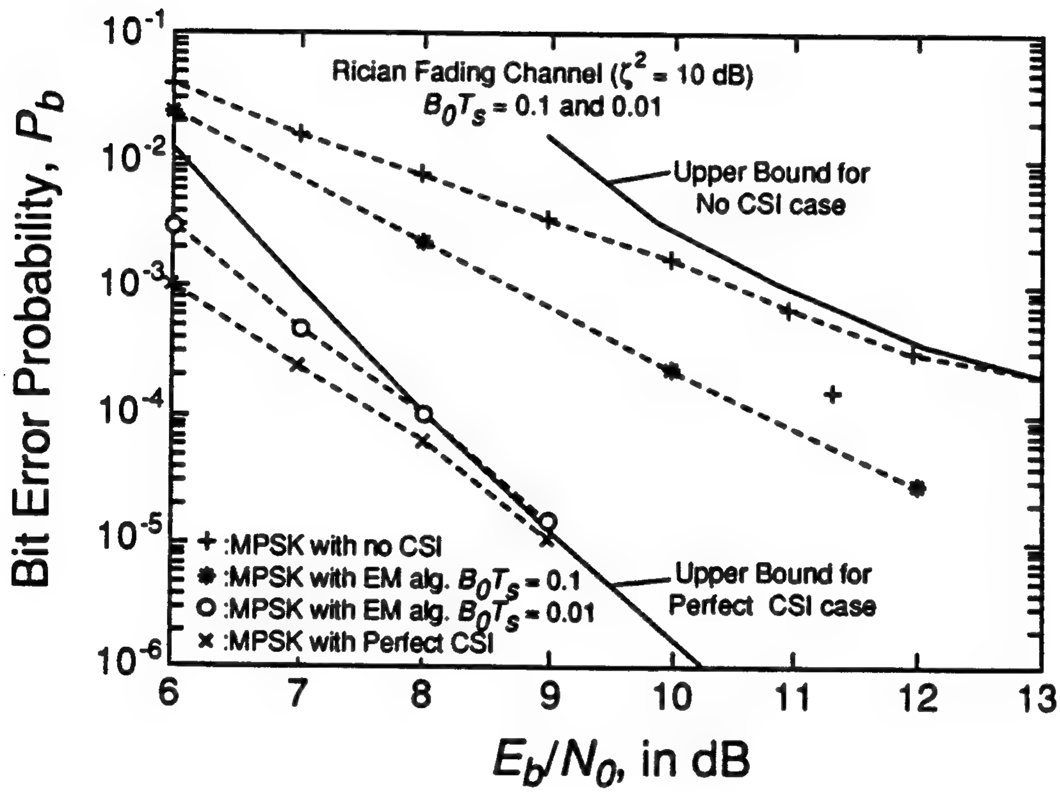

Figure 9
Bit error probability for trellis-coded 8 PSK with code vector (9, 2, 4) and 8 encoder states on the slow-fading Rician channel with $\eta^2 = 10$ dB.

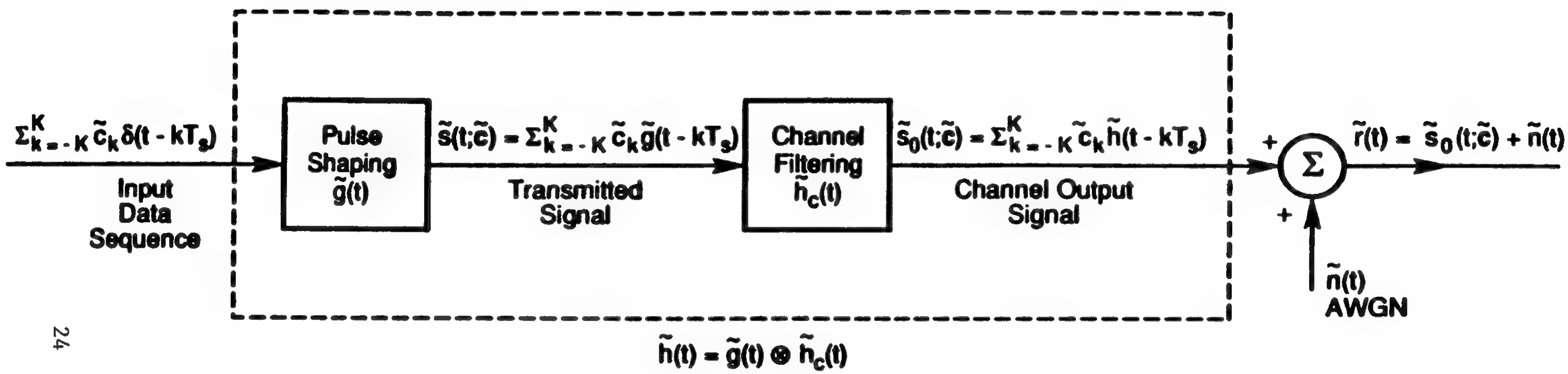

Figure 10
Model for digital transmission over ISI channel.

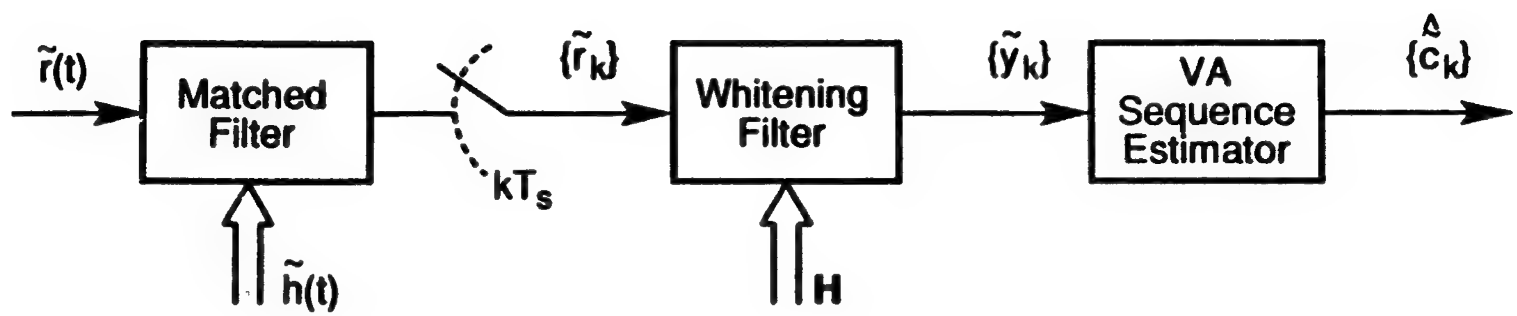

Figure 11
Conventional maximum-likelihood sequence estimator employing the Viterbi Algorithm.

$$\hat{\tilde{\mathbf{x}}}^{(p)} = \tilde{h}_0\hat{\tilde{\mathbf{c}}}^{(p)} + \Lambda\left[\tilde{\mathbf{r}} - \mathbf{H}\hat{\tilde{\mathbf{c}}}^{(p)}\right] \; ; \; p = 0, 1, \ldots, P$$

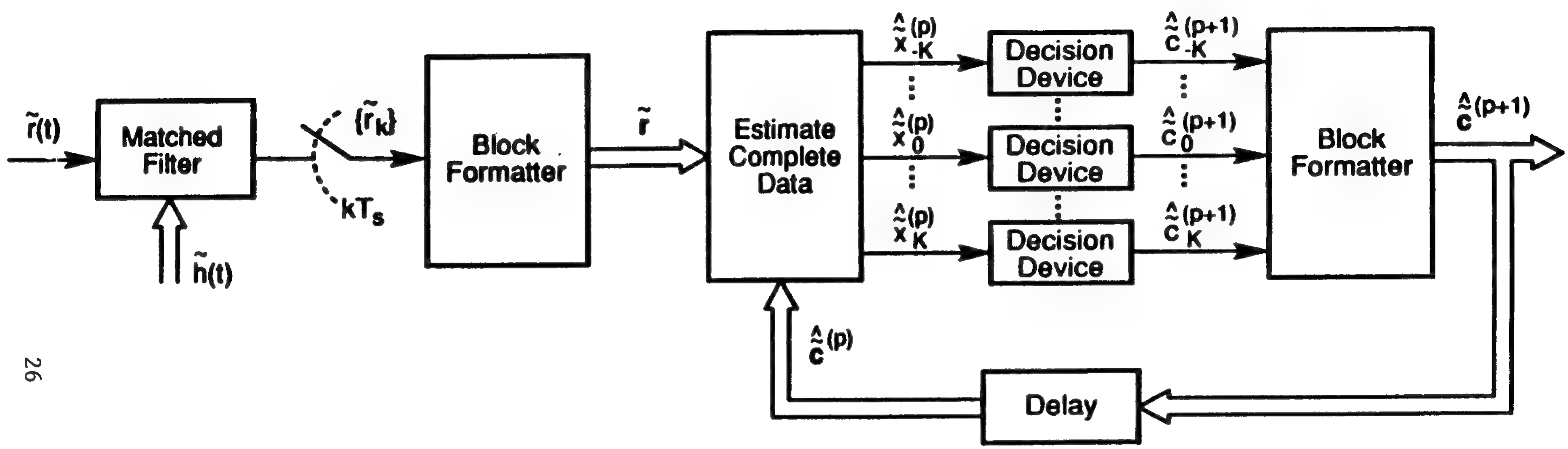

Figure 12
Block diagram of reduced-complexity iterative maximum-likelihood sequence estimator.

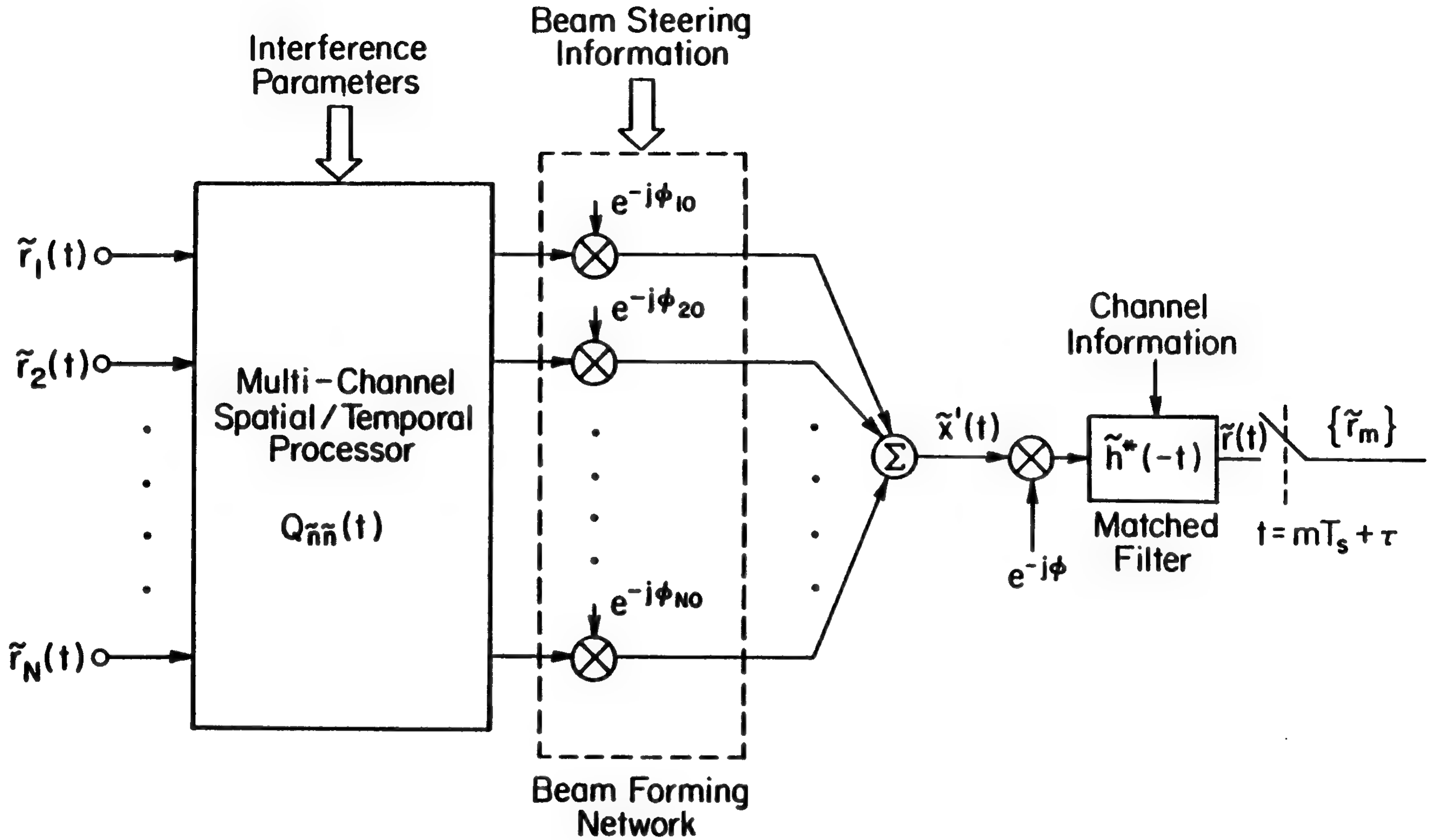

Figure 13
Optimum integrated ML array processor/demodulator for reception in spatially distributed interference environment.

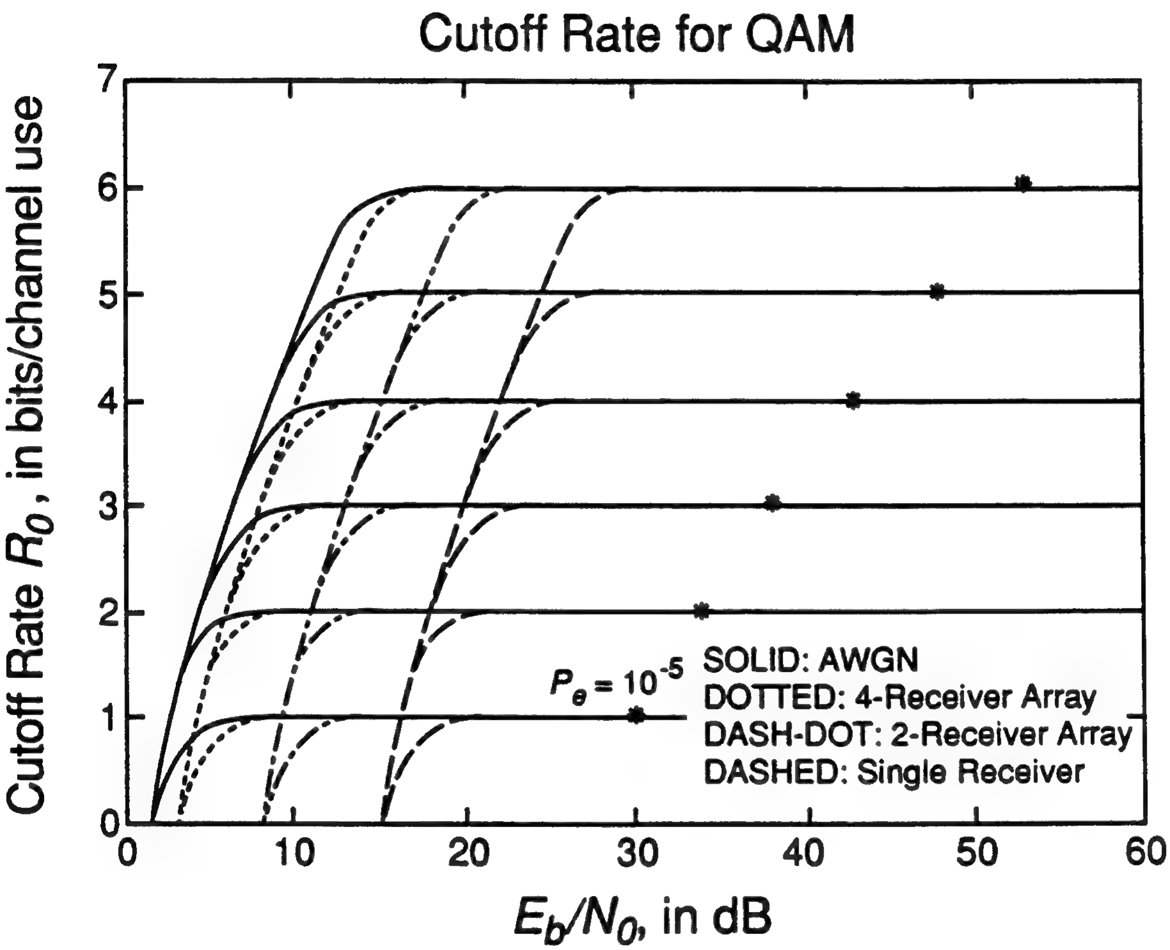

Figure 14
Cutoff rate performance for QAM in AWGN for multielement ML receiver structure with half-wavelength interelement spacing.

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